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Internal Dose Assessment#NCERC Uranium Contamination Event

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Disclaimer

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1 SUMMARY

This report documents internal doses assessed to five LLNL employees from uptakes of highly enriched uranium during operations at the National Criticality Experiments Research Center (NCERC) at the Nevada National Security Site (NNSS). Typically, internal dose assessments are issued separately for each person. However, because this investigation was initiated by routine bioassay sample results for two individuals, and the other affected individuals were not identified until several weeks after the initiating bioassay results were reported, the intake and dose assessments are combined in a single report.

To protect personal data and to ease redaction, individuals are not identified by name in the body of the report and are instead identified according to Table 1 below. These identifiers are consistent with those used in other reports concerning this event, such as the bioassay fact sheets issued by the Joint Laboratory Operations—Nevada (JLON) office.

Table 1: Employee Cross-Reference

Identifier	Employee	LLNL ID#
LLNL-1		
LLNL-2		
LLNL-3		
LLNL-4		
LLNL-5		
LLNL-6		
LLNL-7		
LLNL-8		
LLNL-9		
LLNL-10		
LLNL-11		
LLNL-12		
LLNL-13		

Intakes of highly enriched uranium (HEU) were detected for 5 of the 13 LLNL employees listed above. The highest committed effective dose is assessed to be 0.131 rem for LLNL-1, which is about 3% of the annual occupational dose limit of 5 rem. The highest tissue dose will be received by the extrathoracic airways, which are assessed to receive a committed equivalent dose of 1.444 rem, also about 3% of the annual organ or tissue dose limit of 50 rem.

2 DESCRIPTION OF EVENT

On July 17, 2014, the Bioassay Laboratory notified the Internal Dosimetry Team of preliminary urine bioassay results indicating an intake of enriched uranium for LLNL-1. Upon notification to the Environment, Safety, and Health (ES&H) Team Health Physicist (HP), it was determined that LLNL-1 had handled enriched uranium at NNSS within the past several months, and a follow-up urine sample was requested from the individual on the same day. At the same time, the HP identified two other individuals (LLNL-2 and LLNL-3) who had also been present in the work area. One of them, LLNL-2, had recently submitted a routine urine bioassay sample for plutonium analysis; the Bioassay Laboratory was asked to add uranium analysis to the sample. No follow-up was conducted for LLNL-3 at this time.

The results of the follow-up sample for LLNL-1 and the routine sample for LLNL-2 were received on July 23, 2014. Both results were positive for enriched uranium, confirming an intake for LLNL-1 and strongly indicating an intake for LLNL-2. Around this time, the LLNL HP notified his counterparts at NNSS of the confirmed intakes of enriched uranium, and bioassay monitoring was initiated by National Security Technologies, LLC (NSTec) for several NSTec and Los Alamos National Laboratory (LANL) employees. Further details of the follow-up response by NSTec and LANL are documented in separate reports developed by those organizations. This report will focus on the internal dose assessments for the five LLNL individuals with confirmed HEU intakes resulting from the work at NCERC.

On August 11, 2014, the ES&H Team HP determined that follow-up bioassay sampling was warranted for all LLNL personnel who had been present at NCERC during the most recent criticality experiments in late May and early June of 2014. As a result, spot urine samples were collected from 11 additional LLNL individuals. No intakes were detected for 8 of the 13 LLNL individuals monitored as part of this investigation.

3 MATERIAL INVOLVED

3.1 Source Term

Details of the isotopic composition of the intake material are not readily available. The causal analysis report issued by LANL (and controlled as Unclassified Controlled Nuclear Information, UCNI) indicates that the isotopic composition of enriched uranium present at NCERC varies by source (critical assembly), but it is reasonable and conservative to assume that the intake material is about 93% ^{235}U by mass, originating from the Godiva assembly.

In the absence of specific information, the default HEU mixture in the IMBA Professional Plus internal dose software was used to calculate internal doses. These values are generally consistent with the limited isotopic information in the LANL causal analysis report. The most significant difference is in the mass ratio of ^{236}U/^{235}U, but the difference is negligible since over 95% of the internal doses are actually due to the ^{234}U present in the mix. Table 2 lists the activity and mass fractions of the uranium isotopes present in the default HEU mixture.

Table 2: IMBA Default HEU Mixture

Isotope	Activity fraction	Mass fraction
^{234}U	9.68E-01	1.06E-02
^{235}U	2.97E-02	9.35E-01
^{236}U	1.97E-03	2.07E-03
^{238}U	2.60E-04	5.27E-02

3.2 Radiological Survey Data

In response to the unexpected bioassay results, NSTec and LANL conducted extensive radiological surveys of the NCERC areas where the experiments had been conducted in May. The radiological survey reports indicated that removable contamination levels of up to 60,000 disintegrations per minute (dpm) alpha activity per 100 cm^2 were detected on surfaces in the work area. Based on the radiological survey results, it is reasonable to assume that intakes of enriched uranium occurred when the individuals were either in the immediate work area or in the anteroom. (Since some of this information is UCNI, further details of workplace radiological surveys are documented in references 5 and 6 and are not reproduced in this report.)

4 SUMMARY OF FOLLOW-UP BIOASSAY RESULTS

4.1 Urine bioassay results

Appendix A lists results for all 13 individuals who submitted samples as part of this assessment. Most samples were single void ("spot") urine samples analyzed for ^{238}U and ^{235}U by inductively coupled plasma mass spectrometry (ICP-MS). In an attempt to reduce the burden of follow-up sampling, aliquots for uranium analysis were taken from routine simulated 24-hour samples for those employees who were already enrolled in routine sampling for other work activities. These samples are indicated in Appendix A.

All samples were analyzed by the Bioassay Laboratory's routine "U-ratio" procedure, *Determination of $^{235}U/^{238}U$ Isotope Ratio in Urine by ICP-MS*. This procedure was first developed in 2009 and is now routinely used at LLNL for workers who handle enriched or depleted uranium, since the determination of $^{235}U/^{238}U$ mass ratio in urine samples provides valuable information to distinguish between occupational sources of uranium and natural background sources.

The Bioassay Laboratory provides the calculation of the $^{235}U/^{238}U$ mass ratio with propagation of analytical uncertainty and an indication of whether or not the calculated ratio is indicative of the $^{235}U/^{238}U$ mass ratio expected of natural uranium. In every sample for the five individuals in this report, the calculated $^{235}U/^{238}U$ mass ratio indicated the presence of enriched uranium and confirmed intakes of enriched uranium.

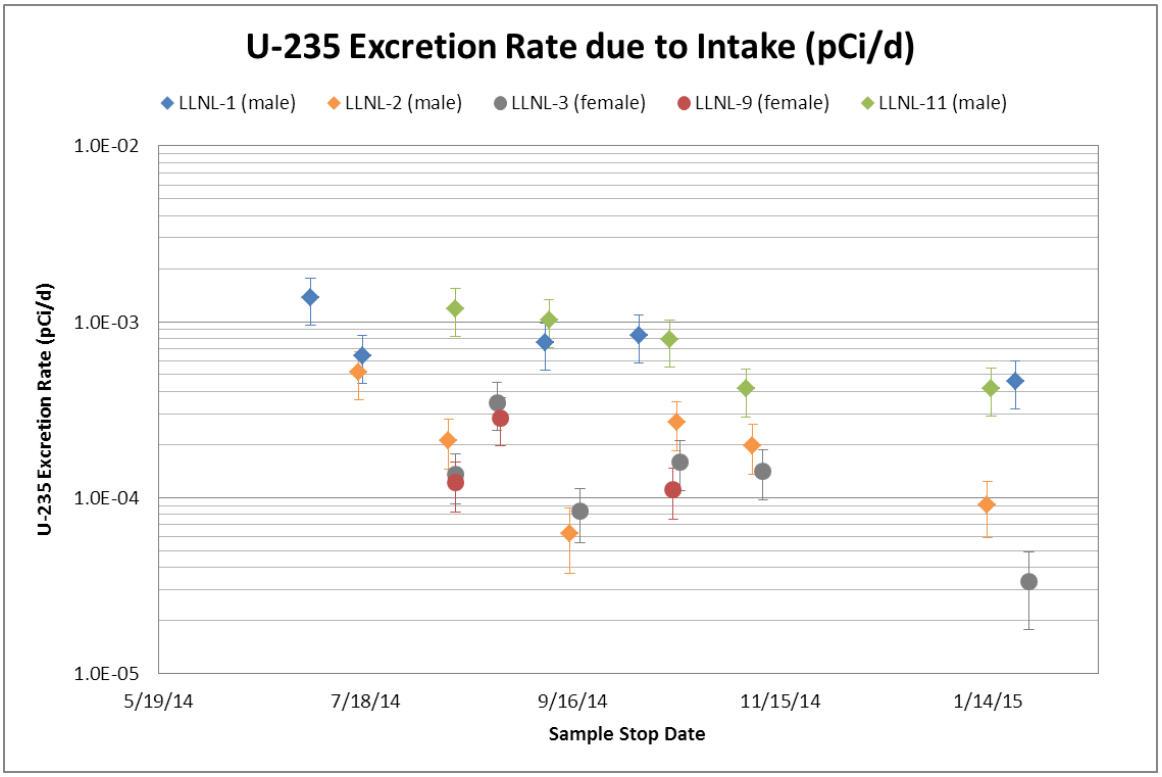
4.2 Background Correction for Environmental Uranium

The uranium present in urine bioassay samples is a combination of two sources: a natural environmental ("background") component and an occupational component. For simplification, it is assumed that the mass ratio of natural uranium is 0.72% ^{235}U by mass, with the balance being ^{238}U (the mass of ^{234}U in natural uranium is considered negligible). For these intakes, it was also assumed that the mass ratio of the intake material was 93.5% ^{235}U by mass, consistent with the IMBA default HEU mix.

Appendix B provides a detailed description of the background correction for environmental uranium in urine bioassay results. For the purposes of this dose assessment, all bioassay results were background-corrected using this method and only the occupational component of the bioassay result was used to assess the intake and dose.

Figure 1 depicts the background-corrected excretion of ^{235}U in urine for the five LLNL employees with confirmed intakes. The error bars represent the analytical uncertainty propagated with an assumed 30% uncertainty to account for biological variations in urinary excretion.

Figure 1: Summary of Background-Corrected Urine Bioassay Results



5 BIOKINETIC AND DOSIMETRIC MODELS

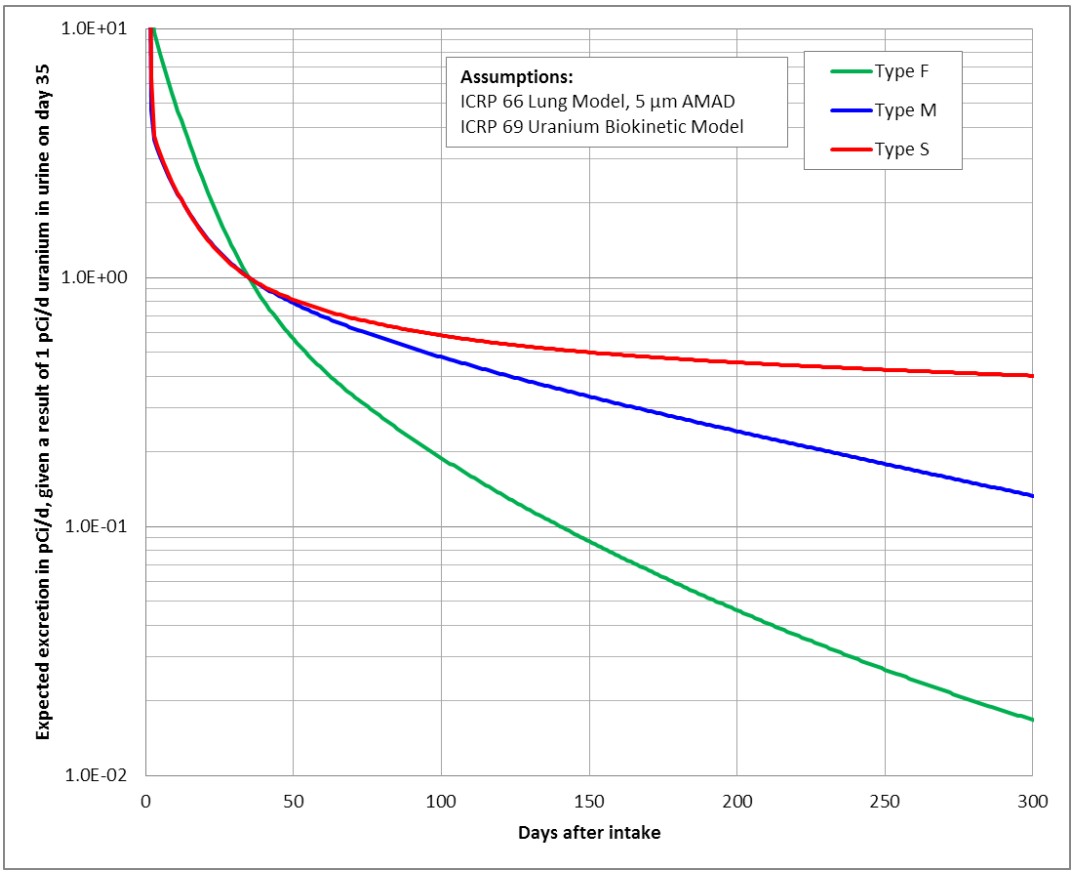
The following biokinetic and dosimetric models were used to estimate the intake and calculate the doses:

- ICRP 66 Human Respiratory Tract Model
- ICRP 69 Biokinetic Model for Uranium
- ICRP 89 Basic Anatomical and Physiological Data

Figure 2 illustrates the predicted urinary excretion rate in picocuries (pCi) per day after an acute inhalation intake of uranium. These curves are based on the biokinetic and dosimetric models listed above and demonstrate that if no information is known about the solubility of the intake material, differentiation between the three solubility types (F—Fast, M—Medium, S—Slow) using only urine results can take several months. In particular, due to biological variations in urinary excretion, differentiation between Type M and Type S uranium using only urine bioassay results may take between 200-300 days following an acute intake.

LANL has initiated a solubility study to determine in vitro dissolution rates for the intake material using simulated lung fluid, but results are not expected to be available until June 2015[†].

Figure 2: Comparison of expected urinary excretion rates for different solubility types of uranium following an acute inhalation intake, based on a urine sample collected 35 days after intake.



[†] Personal communication: Jeff Hoffman (Los Alamos National Laboratory) to Lydia Tai, February 11, 2015.

6 DETERMINATION OF INTAKE PARAMETERS

6.1 Route of Intake

Initially, the route of intake was not known, but assumed to be by acute inhalation. Based on the results of the urine samples collected in November 2014 (about 150-175 days after the intakes), pure ingestion intakes were ruled out. It is possible intakes were by a combination of inhalation and ingestion, but it is reasonably conservative to assume that the route of intake was acute inhalation in all five cases.

6.2 Date of Intake

The dates of intake were also not known initially, but assumed to be during the period of criticality experiments in late May following workplace reviews for the two individuals with the initial positive results. Four of the five LLNL individuals are not based full-time at NNSS and were only on site for a few weeks, which helped narrow the possible intake timeframe. LLNL-1, LLNL-2, and LLNL-3 had all been present in the work areas as early as May 19, 2014, but LLNL-9 and LLNL-11 were not present for these experiments. This discrepancy indicates that the intakes did not occur as a single event, but could have occurred due to resuspension of removable contamination.

Since the earliest possible date LLNL-9 and LLNL-11 were in the facility was June 3, 2014, this date was assumed as the intake date for these two individuals. An intake date of May 28, 2014 was assumed for LLNL-1, LLNL-2, and LLNL-3, since this date provided a better fit to the bioassay results than the most conservative date of May 19, 2014. This assumption is also consistent with the experiment schedule, since experiments and re-entries occurred more frequently during the last week of May than during the week of May 19, 2014.

6.3 Selection of Model Parameters

The typical LLNL internal dose assessment process is to manually vary the weighted mix of solubility types and particle size distributions to achieve the best fit to the bioassay data. In this case, an abbreviated version of this technique was used. Due to the fact that these were low activity intakes, there was large biological variability in excretion rates (i.e., small changes in the amount of natural uranium in a diet would change the sensitivity of the ratio method), which prevented a very good fit to the data. Due to the limited time frame in which the intakes could have occurred, in all cases, minor changes in particle size or intake date made little difference in the final assessed dose.

Therefore, intake dates were assumed as described in Section 6.2 of this report, and IMBA was used to identify the mix of solubility types that provided the best fit to each individual’s data. In all five cases, the mix was weighted essentially 100% toward either Type S or Type M. Bioassay data for LLNL-1, LLNL-2, and LLNL-9 indicated that selection of Type S material provided a better fit. Selection of Type M material provided a better fit to the bioassay data for LLNL-3 and LLNL-11.

Figures 3, 4, and 5 illustrate the bioassay data for LLNL-1, LLNL-2, and LLNL-9, along with the predicted urinary excretion of uranium assuming an intake of 100% Type S material.

Figures 6 and 7 illustrate the bioassay data for LLNL-3 and LLNL-11, along with the predicted urinary excretion of uranium assuming an intake of 100% Type M material.

Figure 3: Comparison of observed and predicted excretion for LLNL-1, assuming an acute inhalation intake on May 28, 2014 of Type S HEU with a particle size distribution of 5 µm AMAD.

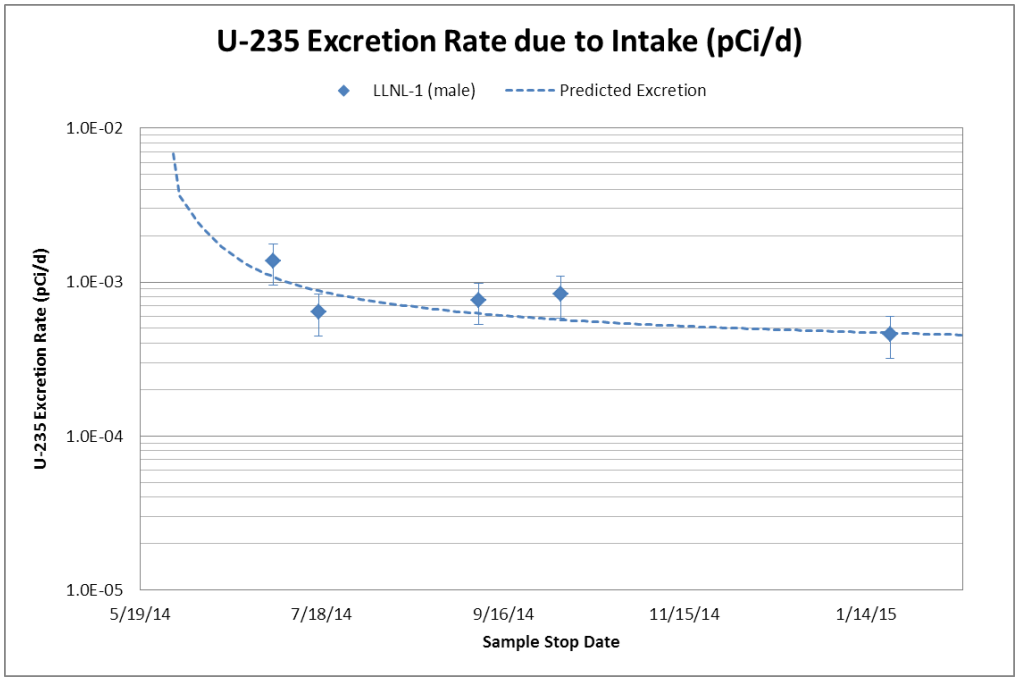


Figure 4: Comparison of observed and predicted excretion for LLNL-2, assuming an acute inhalation intake on May 28, 2014 of Type S HEU with a particle size distribution of 5 µm AMAD.

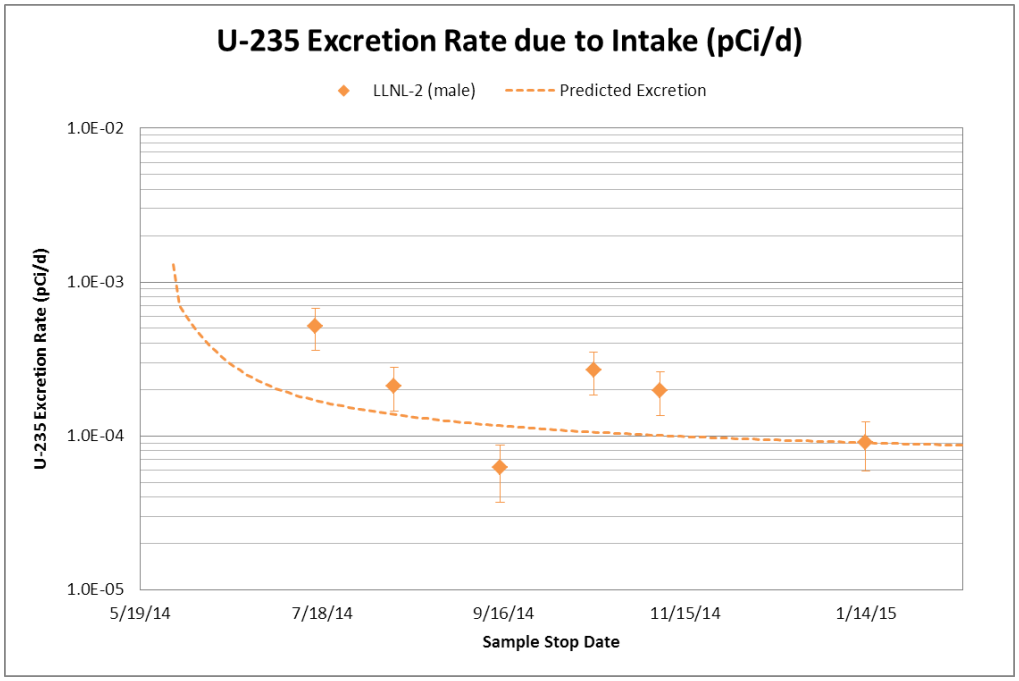


Figure 5: Comparison of observed and predicted excretion for LLNL-9, assuming an acute inhalation intake on June 3, 2014 of Type S HEU with a particle size distribution of 5 µm AMAD.

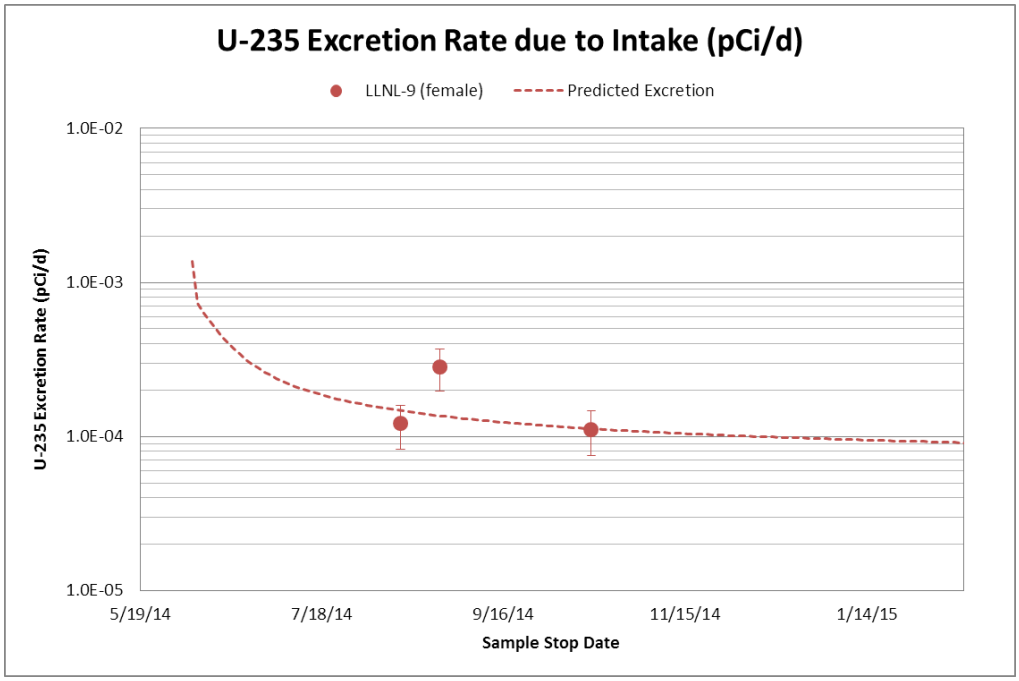


Figure 6: Comparison of observed and predicted excretion for LLNL-3, assuming an acute inhalation intake on May 28, 2014 of Type M HEU with a particle size distribution of 5 µm AMAD.

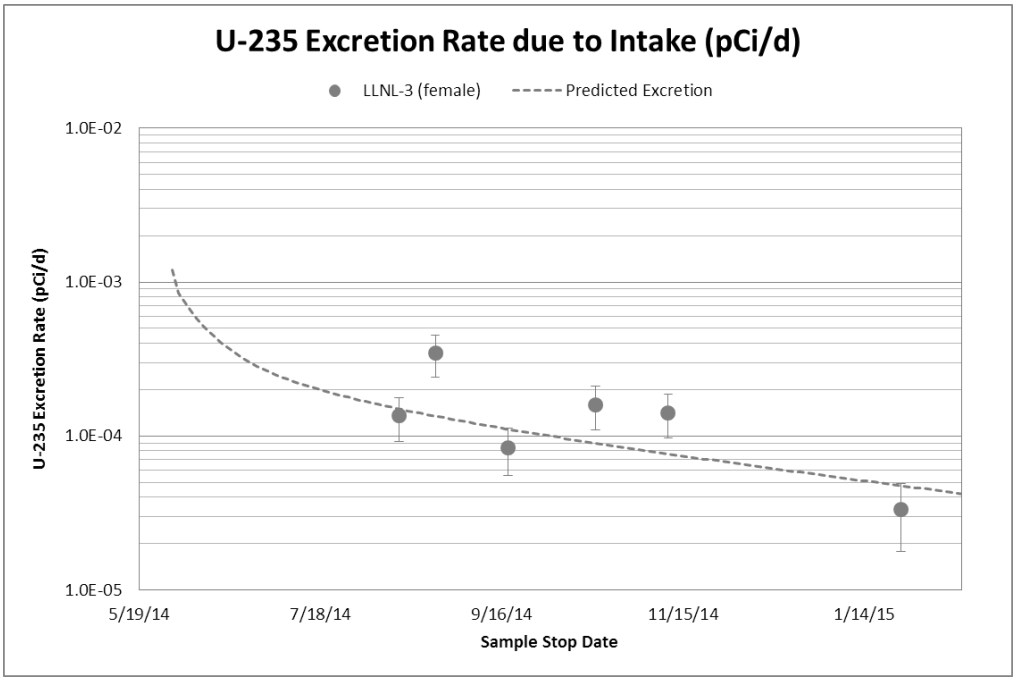
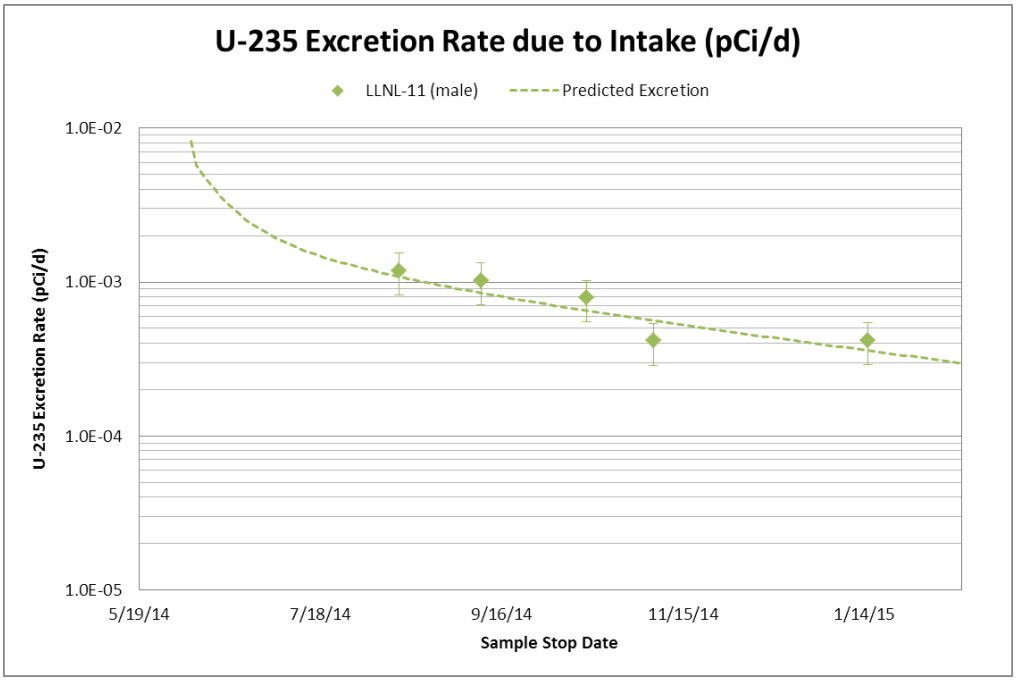


Figure 7: Comparison of observed and predicted excretion for LLNL-11, assuming an acute inhalation intake on June 3, 2014 of Type M HEU with a particle size distribution of 5 µm AMAD.



7 ESTIMATES OF INTAKE

Intakes of ^{235}U were calculated based on the background-corrected urine bioassay results for ^{235}U. The IMBA Professional Plus internal dose program was used to estimate the intakes for each individual using the model parameters described in Section 6 of this report.

The ^{235}U intakes were converted to total intakes of HEU using the activity fractions given in Table 2. Intakes less than 1,000 dpm are rounded to the nearest 10, while intakes greater than 1,000 dpm are rounded to the nearest 100.

Table 3: Summary of Calculated HEU Intakes

	LLNL-1	**LLNL-2**	**LLNL-3**	**LLNL-9**	**LLNL-11**
Solubility Type	Type S	Type S	Type M	Type S	Type M
^{235}U Intake (pCi)	155	29.6	1.07	30.9	7.3
Total HEU Intake (dpm)	**11,600**	**2,200**	**80**	**2,300**	**550**

8 CALCULATION OF DOSES

Dose calculations were performed with the aid of the IMBA Professional Plus internal dose program. IMBA was used to generate the dose coefficients for each tissue and organ for Type S and Type M HEU, using the default HEU mixture as described in Section 3 of this report. The total HEU intakes were determined from the ^{235}U intakes using the following formula:

$$\text{HEU (activity)} = \frac{^{235}\text{U (activity)}}{^{235}\text{U activity fraction in HEU mixture}}$$

Internal doses were calculated using the following formula:

$$\text{Dose (rem)} = \text{HEU intake (pCi)} \cdot \text{Dose Coefficient} \left(\frac{\text{rem}}{\text{pCi}}\right)$$

The 10 CFR 835 tissue weighting factors were used to convert committed equivalent doses to committed effective dose (CED). In the case of Type S uranium, the tissue receiving the highest committed equivalent dose is the extrathoracic airways, normally a remainder tissue. Thus, in accordance with 10 CFR 835, the extrathoracic airways are given a tissue weighting factor of 0.025 and the remainder equivalent dose, calculated using the mass-weighted mean dose of the remaining nine remainder organs and tissues, is given a tissue weighting factor of 0.025.

The CEDs for LLNL-3 and LLNL-11 are assessed to be 0.0003 and 0.002 rem, respectively. Since these are below LLNL's reporting threshold of 0.01 rem, internal doses will not be recorded for these individuals. However, the fact that intakes were detected will be recorded in the LLNL Radiation Exposure Monitoring System (REMS) database and a copy of this report will be filed with their permanent dose records. Assessed doses for LLNL-1, LLNL-2, and LLNL-9 are given in the table below. Since over 95% of the total dose is due to ^{234}U, these doses will be assigned to ^{234}U in REMS.

Table 4: Summary of Doses

	Tissue Weighting Factor (w_T)	**Committed Equivalent Dose to Organ or Tissue (rem)**		
		LLNL-1	**LLNL-2**	**LLNL-9**
Gonads (testes or ovaries)	0.20	0.000	0.000	0.000
Breast tissue	0.05	0.000	0.000	0.000
Red bone marrow	0.12	**0.001**	0.000	0.000
Lungs	0.12	**0.792**	**0.152**	**0.158**
Thyroid	0.05	0.000	0.000	0.000
Bone surfaces	0.01	**0.005**	**0.001**	**0.001**
Colon	0.12	0.000	0.000	0.000
Stomach	0.12	0.000	0.000	0.000
Bladder	0.05	0.000	0.000	0.000
Liver	0.05	**0.001**	0.000	0.000
Esophagus	0.05	0.000	0.000	0.000
Skin	0.01	0.000	0.000	0.000
Extrathoracic airways	0.025	**1.444**	**0.277**	**0.288**
Remainder	0.025	0.000	0.000	0.000
Whole Body (Committed Effective Dose)	**1.00**	**0.131**	**0.025**	**0.026**

9 REFERENCES

1. ICRP, 1994. Human Respiratory Tract Model for Radiological Protection. ICRP Publication 66. Ann. ICRP 24 (1-3).
2. ICRP, 1995. Age-dependent Doses to Members of the Public from Intake of Radionuclides - Part 3 Ingestion Dose Coefficients. ICRP Publication 69. Ann. ICRP 25 (1).
3. ICRP, 2002. Basic Anatomical and Physiological Data for Use in Radiological Protection Reference Values. ICRP Publication 89. Ann. ICRP 32 (3-4).
4. James, A. C., et al., IMBA Professional Plus, version 4.1.55.
5. NSTec Form FRM-0108B, Radiological Survey Report, Survey #14-DAF-06-415, August 18, 2014.
6. Peterson, G., et al., Causal Analysis of the NCERC DAF Uranium Contamination Event, Los Alamos National Laboratory, December 11, 2014. (This document is UCNI.)
7. Wong, C. T., Determination of $^{235}U/^{238}U$ Isotope Ratio in Urine by ICP-MS, Lawrence Livermore National Laboratory, RP-BLAB-303 Rev 0, April 18, 2014.

10 ACRONYMS

AMAD	Activity median aerodynamic diameter
CED	Committed effective dose
dpm	disintegrations per minute
ES&H	Environment, safety, and health
HEU	Highly enriched uranium
HP	Health physicist
ICP-MS	Inductively coupled plasma mass spectrometry
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
JLON	Joint Laboratory Operations—Nevada
LANL	Los Alamos National Laboratory
NCERC	National Criticality Experiments Research Center
NNSS	Nevada National Security Site
NSTec	National Security Technologies, LLC *Management and Operating contractor for the NNSS*
pCi	picocurie (1 pCi = 2.22 dpm)
REMS	Radiation Exposure Monitoring System *LLNL database for documenting all personnel doses*
UCNI	Unclassified Controlled Nuclear Information

Appendix A: Bioassay Results

As discussed in Section 2 of the report, urine samples were received from a total of 13 LLNL individuals. The results for 8 individuals indicated no intakes of enriched uranium. These results are included in Table A.1 below for completeness, but no intakes or doses were assigned to these individuals.

Table A.1: Urine Results as Reported by the LLNL Bioassay Laboratory

	Sample Date	U-238 (µg/L)	U-238 CSU[a] (µg/L)	U-235 (µg/L)	U-235 CSU (µg/L)	U-235/ U-238	CSU	Ratio Description[b,c]
LLNL-1	7/2/14[d]	6.070E-03	1.343E-04	4.370E-04	9.238E-06	6.720E-02	2.055E-03	ENRICHED
	7/17/14	4.780E-03	1.261E-04	2.200E-04	6.786E-06	4.400E-02	1.786E-03	ENRICHED
	9/8/14	8.170E-03	1.478E-04	2.780E-04	7.441E-06	3.290E-02	1.063E-03	ENRICHED
	10/5/14	1.660E-02	2.017E-04	3.610E-04	8.379E-06	2.130E-02	5.577E-04	ENRICHED
	1/22/15[d]	9.780E-03	1.581E-04	2.030E-04	6.594E-06	2.030E-02	7.378E-04	ENRICHED
LLNL-2	7/16/14[d]	5.210E-03	1.288E-04	1.870E-04	6.413E-06	3.470E-02	1.465E-03	ENRICHED
	8/11/14	4.350E-03	1.233E-04	9.270E-05	5.348E-06	2.090E-02	1.341E-03	ENRICHED
	9/15/14	4.050E-03	1.214E-04	4.740E-05	4.836E-06	1.160E-02	1.230E-03	ENRICHED
	10/16/14[d]	4.790E-03	1.262E-04	1.120E-04	5.566E-06	2.290E-02	1.285E-03	ENRICHED
	11/7/14	2.740E-03	1.130E-04	7.690E-05	5.169E-06	2.730E-02	2.153E-03	ENRICHED
	1/14/15[d]	2.460E-03	1.112E-04	4.410E-05	4.798E-06	1.760E-02	2.075E-03	ENRICHED
LLNL-3	8/13/14	3.050E-03	1.150E-04	7.410E-05	5.137E-06	2.370E-02	1.872E-03	ENRICHED
	8/25/14	1.040E-02	1.621E-04	2.080E-04	6.650E-06	1.960E-02	6.974E-04	ENRICHED
	9/18/14	5.680E-03	1.319E-04	7.350E-05	5.131E-06	1.280E-02	9.397E-04	ENRICHED
	10/17/14	4.920E-03	1.270E-04	9.720E-05	5.398E-06	1.940E-02	1.186E-03	ENRICHED
	11/10/14	2.400E-03	1.109E-04	7.200E-05	5.114E-06	2.910E-02	2.468E-03	ENRICHED
	1/26/15	1.730E-03	1.066E-04	2.540E-05	4.587E-06	1.450E-02	2.761E-03	ENRICHED
LLNL-4	8/13/14	2.450E-03	1.112E-04	2.350E-05	4.566E-06	9.500E-03	1.895E-03	NATURAL
LLNL-5	8/13/14	3.150E-03	1.157E-04	2.340E-05	4.564E-06	7.370E-03	1.464E-03	NATURAL
LLNL-6	8/13/14	8.820E-03	1.519E-04	6.450E-05	5.029E-06	7.260E-03	5.797E-04	NATURAL
LLNL-7	8/13/14	1.110E-02	1.665E-04	9.010E-05	5.318E-06	8.050E-03	4.904E-04	NATURAL
LLNL-8	8/19/14	8.330E-03	1.488E-04	5.980E-05	4.976E-06	7.130E-03	6.066E-04	NATURAL
LLNL-9	8/13/14	2.950E-03	1.144E-04	6.800E-05	5.068E-06	2.250E-02	1.893E-03	ENRICHED
	8/26/14	3.950E-03	1.208E-04	1.380E-04	5.859E-06	3.380E-02	1.766E-03	ENRICHED
	10/15/14	2.530E-03	1.117E-04	6.120E-05	4.992E-06	2.360E-02	2.190E-03	ENRICHED
LLNL-10	8/20/14	4.870E-03	1.267E-04	3.580E-05	4.705E-06	7.300E-03	9.776E-04	NATURAL
LLNL-11	8/13/14	1.040E-02	1.621E-04	4.180E-04	9.023E-06	3.860E-02	1.029E-03	ENRICHED
	9/9/14	1.090E-02	1.653E-04	3.740E-04	8.526E-06	3.320E-02	9.082E-04	ENRICHED
	10/14/14	8.380E-03	1.491E-04	2.880E-04	7.554E-06	3.320E-02	1.053E-03	ENRICHED
	11/5/14	3.910E-03	1.205E-04	1.480E-04	5.972E-06	3.650E-02	1.852E-03	ENRICHED
	1/15/15	4.580E-03	1.248E-04	1.530E-04	6.029E-06	3.230E-02	1.549E-03	ENRICHED
LLNL-12	8/13/14	1.990E-03	1.082E-04	9.860E-06	4.411E-06	4.930E-03	2.222E-03	NATURAL
LLNL-13	8/22/14	1.300E-02	1.787E-04	1.040E-04	5.475E-06	7.940E-03	4.318E-04	NATURAL

[a] CSU: Combined standard uncertainty (1σ).
[b] ENRICHED: Ratio exceeds the upper limit for natural uranium.
[c] NATURAL: Ratio appears to be natural uranium. No intakes were detected for these individuals.
[d] Aliquots for uranium analysis were taken from routine simulated 24-hour samples. All other samples were single-void "spot" samples.

Appendix B: Background Correction for Environmental Uranium

The urine sample results in Appendix A demonstrate that the measured mass ratios in the urine samples are much lower than the assumed 93.5% enrichment of the intake material, with the highest mass ratio in urine observed to be about 6.7%. The implication is that the total uranium present in urine is the sum of the excretion from an occupational intake of enriched uranium and the excretion from natural background (dietary) sources of uranium. That is,

$$\mathrm{U_{total}} = \mathrm{U_{intake}} + \mathrm{U_{background}}$$

The ICP-MS analysis for uranium in urine gives both ^{235}U and ^{238}U results, so each of those results is also assumed to be the sum from the two sources:

$$\mathrm{U235_{total}} = \mathrm{U235_{intake}} + \mathrm{U235_{background}}$$

$$\mathrm{U238_{total}} = \mathrm{U238_{intake}} + \mathrm{U238_{background}}$$

Definitions

$\mathrm{U238}_T$	=	total U-238 concentration reported by the Bioassay Laboratory (µg/L)
$\mathrm{U235}_T$	=	total U-235 concentration reported by the Bioassay Laboratory (µg/L)
CSU_{238}	=	combined standard uncertainty (1σ) for total U-238 concentration (µg/L)
CSU_{235}	=	combined standard uncertainty (1σ) for total U-235 concentration (µg/L)
$\mathrm{U238}_b$	=	the portion of $\mathrm{U238}_T$ resulting from natural uranium (µg/L)
$\mathrm{U235}_b$	=	the portion of $\mathrm{U235}_T$ resulting from natural uranium (µg/L)
$\mathrm{U238}_i$	=	the portion of $\mathrm{U238}_T$ resulting from an occupational intake (µg/L)
$\mathrm{U235}_i$	=	the portion of $\mathrm{U235}_T$ resulting from an occupational intake (µg/L)
E_i	=	fraction of U-235 by mass in the intake material, assuming $E = \frac{\mathrm{U235}}{\mathrm{U235+U238}}$
E_B	=	fraction of U-235 by mass in natural uranium, assumed to be $0.0072 = \frac{\mathrm{U235}_b}{\mathrm{U235}_b+\mathrm{U238}_b}$

The following calculations are used by the Bioassay Laboratory to determine the ^{235}U/^{238}U mass ratio and to set the flag for enriched uranium:

R	=	calculated fraction of U-235 by mass observed in the urine; $R = \frac{\mathrm{U235}_T}{\mathrm{U235}_T+\mathrm{U238}_T}$
CSU_R	=	error in the calculated fraction of U-235 by mass observed in the urine; $\mathrm{CSU}_R = R\sqrt{\left(\frac{\mathrm{CSU}_{235}}{\mathrm{U235}_T}\right)^2 + \left(\frac{\mathrm{CSU}_{238}}{\mathrm{U238}_T}\right)^2}$
"Flag"	=	R is "flagged" as above the upper limit for natural uranium if: $R - 1.96 \cdot \mathrm{CSU}_R > 0.0072$

If a urine ratio result, taking into account analytical uncertainty, is determined to be above the upper limit for natural uranium, it is indicative of a potential intake of enriched uranium and the following process is used to determine the contributions to the measured mass concentration results from the occupational intake of processed uranium and from background intake of natural uranium.

(1) Assume the mass enrichment of natural uranium is given by $E_b = \frac{\mathrm{U235}_b}{\mathrm{U235}_b + \mathrm{U238}_b} = 0.0072$ (treating $\mathrm{U234}_b$ as negligible). Rearrange to obtain $\mathrm{U238}_b$:

$$0.0072 = \frac{\mathrm{U235}_b}{\mathrm{U235}_b + \mathrm{U238}_b}$$

$$0.0072(\mathrm{U235}_b + \mathrm{U238}_b) = \mathrm{U235}_b$$

$$0.0072 \cdot \mathrm{U238}_b = \mathrm{U235}_b - 0.0072 \cdot \mathrm{U235}_b$$

$$\mathrm{U238}_b = \left(\frac{0.9928}{0.0072}\right)\mathrm{U235}_b$$

(2) Assume that $\mathrm{U235}_T = \mathrm{U235}_b + \mathrm{U235}_i$ and rearrange to obtain $\mathrm{U235}_i$:

$$\mathrm{U235}_i = \mathrm{U235}_T - \mathrm{U235}_b$$

(3) Assume that $\mathrm{U238}_T = \mathrm{U238}_b + \mathrm{U238}_i$ and rearrange to obtain $\mathrm{U238}_i$:

$$\mathrm{U238}_i = \mathrm{U238}_T - \mathrm{U238}_b$$

(4) Assume the mass enrichment of the intake material is given by $E_i = \frac{\mathrm{U235}_i}{\mathrm{U235}_i + \mathrm{U238}_i}$.

(5) Substitute equations (2) and (3) into equation (4):

$$E_i = \frac{\mathrm{U235}_T - \mathrm{U235}_b}{\mathrm{U235}_T - \mathrm{U235}_b + \mathrm{U238}_T - \mathrm{U238}_b}$$

(6) Substitute equation (1) into equation (5):

$$E_i = \frac{\mathrm{U235}_T - \mathrm{U235}_b}{\mathrm{U235}_T - \mathrm{U235}_b + \mathrm{U238}_T - \left(\frac{0.9928}{0.0072}\right)\mathrm{U235}_b}$$

(7) Solve for $\mathrm{U235}_b$:

$$E_i = \frac{\mathrm{U235}_T - \mathrm{U235}_b}{\mathrm{U235}_T - \mathrm{U235}_b + \mathrm{U238}_T - \left(\frac{0.9928}{0.0072}\right)\mathrm{U235}_b}$$

$$E_i\left[\mathrm{U235}_T - \mathrm{U235}_b + \mathrm{U238}_T - \left(\frac{0.9928}{0.0072}\right)\mathrm{U235}_b\right] = \mathrm{U235}_T - \mathrm{U235}_b$$

$$E_i \cdot \mathrm{U235}_T + E_i \cdot \mathrm{U238}_T - \mathrm{U235}_T = E_i \cdot \mathrm{U235}_B + E_i\left(\frac{0.9928}{0.0072}\right)\mathrm{U235}_b - \mathrm{U235}_b$$

$$E_i \cdot \mathrm{U235}_T + E_i \cdot \mathrm{U238}_T - \mathrm{U235}_T = \mathrm{U235}_b\left[E_i + E_i\left(\frac{0.9928}{0.0072}\right) - 1\right]$$

$$\mathrm{U235}_b = \frac{(E_i \cdot \mathrm{U235}_T) + (E_i \cdot \mathrm{U238}_T) - \mathrm{U235}_T}{\left[E_i \cdot \left(\frac{0.9928}{0.0072}\right)\right] + E_i - 1}$$

(8) Solve for $\mathrm{U235}_i$:

$$\mathrm{U235}_i = \mathrm{U235}_T - \mathrm{U235}_b$$

These background-corrected values of $U235_i$ were used for the intake and dose assessments for the five individuals in this report. Table B.1 lists the results for ^{238}U and ^{235}U reported by the Bioassay Laboratory and the corresponding background-corrected values for ^{235}U in units of µg/L and pCi/d.

The daily urine excretion rates from ICRP Publication 89 (1.6 L/d for males and 1.2 L/d for females) were used in the conversion to daily excretion.

Table B.1: Background-Corrected Urine Results

	Sample Stop Date	$U238_T$ (µg/L)	$U235_T$ (µg/L)	$U235_i$ (µg/L)	$U235_i$ (pCi/d)
LLNL-1	7/2/14	6.070E-03	4.370E-04	3.932E-04	1.361E-03
	7/17/14	4.780E-03	2.200E-04	1.854E-04	6.417E-04
	9/8/14	8.170E-03	2.780E-04	2.189E-04	7.574E-04
	10/5/14	1.660E-02	3.610E-04	2.407E-04	8.331E-04
	1/22/15	9.780E-03	2.030E-04	1.321E-04	4.573E-04
LLNL-2	7/16/14	5.210E-03	1.870E-04	1.493E-04	5.167E-04
	8/11/14	4.350E-03	9.270E-05	6.119E-05	2.117E-04
	9/15/14	4.050E-03	4.740E-05	1.804E-05	6.242E-05
	10/16/14	4.790E-03	1.120E-04	7.730E-05	2.675E-04
	11/7/14	2.740E-03	7.690E-05	5.706E-05	1.975E-04
	1/14/15	2.460E-03	4.410E-05	2.627E-05	9.092E-05
LLNL-3	8/13/14	3.050E-03	7.410E-05	5.201E-05	1.350E-04
	8/25/14	1.040E-02	2.080E-04	1.326E-04	3.443E-04
	9/18/14	5.680E-03	7.350E-05	3.233E-05	8.390E-05
	10/17/14	4.920E-03	9.720E-05	6.155E-05	1.598E-04
	11/10/14	2.400E-03	7.200E-05	5.462E-05	1.418E-04
	1/26/15	1.730E-03	2.540E-05	1.286E-05	3.338E-05
LLNL-9	8/13/14	2.950E-03	6.800E-05	4.663E-05	1.210E-04
	8/26/14	3.950E-03	1.380E-04	1.094E-04	2.840E-04
	10/15/14	2.530E-03	6.120E-05	4.288E-05	1.113E-04
LLNL-11	8/13/14	1.040E-02	4.180E-04	3.428E-04	1.186E-03
	9/9/14	1.090E-02	3.740E-04	2.951E-04	1.021E-03
	10/14/14	8.380E-03	2.880E-04	2.274E-04	7.868E-04
	11/5/14	3.910E-03	1.480E-04	1.197E-04	4.143E-04
	1/15/15	4.580E-03	1.530E-04	1.199E-04	4.148E-04